Measurement of Azimuthal Anisotropy at RHIC-PHENIX

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Abstract. The transverse momentum ($p_T$) and centrality dependence of the azimuthal anisotropy of second harmonics ($v_2$) are measured for charged hadron species at various collision systems and energies such as $\sqrt{s_{NN}} = 62.4$ and 200 GeV in Cu + Cu and Au + Au collisions and at $\sqrt{s_{NN}} = 200$ GeV in Cu + Au collisions by the PHENIX experiment at RHIC. The higher order anisotropy ($v_3$) are also measured for charged hadron at $\sqrt{s_{NN}} = 200$ GeV in Cu + Cu, Au + Au and Au + Cu collisions. From these systematic study, we found that the all results are consistent with eccentricity scaling, quark number + KE\textsubscript{T} scaling and $N^{1/3}_{\text{part}}$ scaling except at small $N_{\text{part}}$ in Cu + Cu at 62.4 GeV. Taking these scaling (quark number, KE\textsubscript{T}, eccentricity and $N^{1/3}_{\text{part}}$) into account, there is a universal scaling for $\pi/K/p v_2$ with different energies, collision sizes and particle species.

1 Introduction

Relativistic heavy ion collisions have been considered as a unique way to create and study the quark-gluon plasma (QGP), where the quarks and gluons are de-confined. The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory was constructed to create and study the QGP. Azimuthal anisotropy of produced particles in relativistic heavy ion collisions is a powerful probe for investigating the characteristics of the QGP. Especially the strength of the elliptic anisotropy ($v_2$), which is defined by the second harmonics of Fourier expansion for the azimuthal distribution of the produced particles with respect to the reaction plane, is expected to be sensitive to the early stage of heavy ion collisions. At non-central collision, the overlap region is geometrically anisotropic, like an almond shape. When the produced matter has small mean free path, interacting each other enough to reach local thermalization, it creates pressure gradient. The geometrical anisotropy transfers to the anisotropy in the momentum phase space as flow because of this pressure gradient, and $v_2$ indicates the strength of this elliptic flow. Thus, the measured $v_2$ reflects the equation of state of the dense matter such as QGP, produced in the collisions. Recently the measurement of the triangle anisotropy ($v_3$) has also drawn scientific attention because most of it are expected to be created by the participant fluctuations in Au + Au and the estimation of the strength of the participant fluctuations strongly depends on theoretical models at initial conditions. Therefore, $v_3$ is expected to be able to put some restriction on initial condition models [3]. On the other hand, as same as $v_2$, $v_3$ should also develop with the pressure gradient at QGP. The important thing here is since the produced particles randomly emit before thermalization, the geometrical anisotropy decreases with time. Therefore, to let the geometrical anisotropy make elliptic and triangular flow, the thermalization should be occurred very early stage before the geometrical anisotropy is totally gone.

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2 Motivation

One of the most remarkable findings at RHIC is that the strength of \( v_2 \) can be described well by hydro-dynamical models in the low transverse momentum region (~ 1 GeV/c) [1]. In the intermediate transverse momentum region (1 ~ 4 GeV/c), \( v_2 \) is consistent with \( n_q \) and KE \( T \) (\( = m_T - m_0 \)) scaling, and the result supports a quark-recombination model [2]. The matter produced in the high energy heavy ion collision is expected to undergo several stages from the initial hard scattering to the final hadron emission. When the matter reaches thermalization and QGP is created, we expect hydro-dynamical behavior at quark level. Because experimentally we cannot see the QGP directly, we need a comprehensive understanding from thermalization through hadronization to freeze-out. The elliptic flow is expected to be created at QGP stage by pressure gradient, but it is important to note whenever the matter interacts with each other, there is a possibility to change \( v_2 \). [4]

For a more comprehensive understanding of azimuthal anisotropy, we have carried out systematic measurements of \( v_2 \), by measuring \( v_2 \) for identified charged hadrons in Au + Au and Cu + Cu collisions at \( \sqrt{S_{NN}} = 200 \) and in Au + Au at \( \sqrt{S_{NN}} = 62.4 \) GeV and also for inclusive charged hadrons in Au + Au and Cu + Cu at \( \sqrt{S_{NN}} = 200 \) and 62.4 GeV. We have studied the dependence on collision energy, size and species of the produced particles comparing the \( \sqrt{S_{NN}} = 2.76 \) TeV data from LHC. [9] Moreover, we measured \( v_2 \) for inclusive and identified charged hadrons in Cu + Au and \( v_2 \) for inclusive charged hadrons in Au + Au and Cu + Au at \( \sqrt{S_{NN}} = 200 \). To study the detailed behavior of flow measurement, we examine the scalings to these results. We had expected that \( v_3 \) at Cu + Au is larger than that at Au + Au because Cu + Au collision provides additional triangular anisotropy at collision geometry while \( v_3 \) in Au + Au comes from initial fractuations.

3 Results

In Au+Au collisions, the values of \( v_2 \) as a function of \( p_T \) agree well at \( \sqrt{S_{NN}} = 39, 62.4 \) and 200 GeV for measured centralities, 10-20, 20-30, 30-40 and 40-50%. However, the \( v_2 \) at 7.7 GeV is much lower than these. This results may indicate the energy between 7.7 and 39 is the region which switch from partonic flow to hadronic flow. We also compared the results of \( \sqrt{S_{NN}} = 2.76 \) TeV data in Pb+Pb at LHC-ALICE, and it was found that \( v_2 \) at 2.76 TeV is very similar to the \( v_2 \) at 200 GeV especially at low \( p_T \). [9]

Next, we compared different system size of collisions such as Au + Au, Cu + Cu, Pb + Pb and Cu + Au at \( \sqrt{S_{NN}} = 200 \) GeV, 62.4 GeV and 2.76 TeV as a function of \( N_{part} \). The values of \( v_2 \) agree well at \( \sqrt{S_{NN}} = 200 \) GeV, 62.4 GeV and 2.76 TeV in Au + Au, but have clear differences between Cu + Cu and Au + Au, and Cu + Au results are between Cu + Cu and Au + Au. This is natural because the different nucleus collisions such as Cu + Cu, Au + Au and Cu + Au have different initial geometrical eccentricities at the same \( N_{part} \). [10, 11] Normalizing \( v_2 \) by eccentricity, \( e \), (eccentricity scaling), all results follow one curve therefore, \( v_2 \) is scaled by the eccentricity at the same \( N_{part} \). Here, we use the participant eccentricity, which includes the effect of participant fluctuations [5]. The values of \( v_2/e \) are not a constant, therefore, \( v_2 \) can be normalized by \( e \) at the same \( N_{part} \), but \( N_{part} \)-dependence still remains. Looking close to this dependence we empirically found that \( v_2/e \) is proportional to \( N_{part}^{1/3} \). This \( N_{part}^{1/3} \) works in Au + Au, Cu + Cu collisions[10] and in Pb + Pb[9] and in Cu + Au [11] as shown in Figure 1. Including results of \( \sqrt{S_{NN}} = 2.76 \) TeV, \( v_2/(e \cdot N_{part}^{1/3}) \) is independent of the collision systems except for small \( N_{part} \) in Cu+Cu at \( \sqrt{S_{NN}} = 62.4 \) GeV.

One of the most famous results on RHIC \( v_2 \) measurement is that the \( v_2 \) for quark number(\( n_q \)) + KE \( T \) scaling in Au+Au at \( \sqrt{S_{NN}} = 200 \) GeV [2] The \( n_q \) scaling is consistent to the recombination model which assumes the quark level flow at QGP phase, and the KE \( T \) scaling has been considered to be able
to subtract the difference of different particle $v_2$ at low $p_T$ which is caused due to the radial flow effect. In Au+Au 200GeV collisions at PHENIX experiment, the large statistics and new detector allowed us to see that the both $n_q$ and KE$_T$ scaling works very well on various particle species including $\phi$, $\Lambda$ and deuteron, and even to see the break point of this scaling at KE$_T = 1$ GeV as shown in [8]. Above this $p_T$ region, one can expect other mechanism is dominant to create $v_2$. For the systematic study, we also measured particle identified $v_2$ in Au+Au at $\sqrt{s_{NN}} = 62.4$ GeV and in Cu+Cu and at $\sqrt{s_{NN}} = 200$ GeV. It is found that $v_2$ in Au+Au at 62.4 GeV is also consistent with $n_q$ + KE$_T$ scaling. Moreover, the $n_q$ + KE$_T$ scaling mostly works out in Cu+Cu at $\sqrt{s_{NN}} = 200$ GeV for central collisions. There are the small discrepancy from the KE$_T$ scaling at peripheral collisions at low $p_T$ and the discrepancy from the KE$_T$ scaling depends on $N_{\text{part}}$. The detailed quantitative comparison are written in [10]. Comparing between $\pi$ and proton, the results indicate the larger $N_{\text{part}}$ produces more shift for proton to higher $p_T$ based on $\pi$. This $N_{\text{part}}$ dependence of KE$_T$ scaling behavior for the $v_2$ is explained by the radial flow effect with blast wave model in [8]. Additionally, KE$_T$ scaling does not work out at $\sqrt{s_{NN}} = 2.76$ TeV. Proton $v_2$ is shifted to higher $p_T$ compared with $\pi$ more than RHIC results.[9] We also measured particle identified $v_2$ for $\pi/K/p$ in Au+Au at $\sqrt{s_{NN}} = 200$ GeV. Mass ordering can be seen at low $p_T$ and baryon and meson splitting are also observed at mid $p_T$ which seems to be consistent to $n_q$ scaling.[12]

In addition to the fact that $v_2(p_T)$ is consistent at $\sqrt{s_{NN}} = 39 - 200$ GeV, $v_2$ normalized by $n_q$ + KE$_T$, eccentricity, and $N_{\text{part}}^{1/3}$ scaling follows a universal curve as shown in the right panel of Figure 2. This figure includes the 45 curves for $\pi/K/p$ in Au+Au at $\sqrt{s_{NN}} = 200$ GeV, in Au+Au at $\sqrt{s_{NN}} = 62.4$ GeV and in Cu+Cu at $\sqrt{s_{NN}} = 200$ GeV for the five centrality bins from 0 - 50% in 10% steps. The combined data is fit with a single 3rd-order-polynomial, producing a $\chi^2/\text{NDF} = 1034/490 = 2.11$ (including both statistical and systematic uncertainties). [10] This is a universal scaling for

![Figure 1. $v_2$ vs. $p_T$ for charged hadron in Au+Au, Cu+Cu and Cu+Au at $\sqrt{s_{NN}} = 200$ GeV at indicated centrality bin in each panel. [9, 11, 12]](image-url)
v2 with different energies, collision sizes and particle species, and it indicates that v2 is determined not only by the geometrical eccentricity but also by the size of collision. This scaling assume that differential v2 is consistent above 39 GeV while "v2/ε vs. (1/S)(dN/dy)" scaling plotted in [7] assumes that the higher collision energy produces higher v2. Therefore, this N1/3 part scaling works better for the differential v2 at PHENIX results. The size dependence of v2 can be understood as thermal freeze-out nature of produced particles based on hydrodynamical behavior, which is different from that of chemical freeze-out. [8] Moreover, this v2/(ε N1/3 part · nq ) scaling is consistent with v3 results in Au + Au and Cu + Au for inclusive charged hadrons.

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References